ロケットエンジン用液体酸素ターボポンプの共鳴キャビテーションサージに関する研究

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論文内容要旨

This paper clarifies the mechanism of acoustic cavitation surge which occurred during the development test for the improved liquid oxidizer turbopump of the first stage engine (LE-7A engine) of the H-IIA rocket. Consequently, the result of the study contributed to the effective development of the liquid oxidizer turbopump and the successful flights of launch vehicles.

Launch vehicles are designed to minimize their dry mass in order to obtain better performance. As propellant tanks are major components of a rocket, decreasing their weight is a very effective way of reducing dry mass. Decreasing the pressure in a tank allows thinner tank walls to contribute to the efficiency of a rocket system. On the other hand, when the pressure in the tank is decreased, the inlet pressure in the turbopump of the rocket engine is decreased and the resultant cavitation in the turbopump inducer causes cavitation instabilities. Cavitation surge (auto-oscillation), i.e., one type of cavitation instability, was studied in the 1960s in relation to POGO instability, which is caused by the interaction between a rocket structure and a rocket propulsion system. More recently the dynamic transfer function of the inducer has been investigated to evaluate the stability of cavitation surge. Moreover, the pump system, including tank, pipes, pump and valves, has been modeled, and the stability of the system has been evaluated. There are several types of instabilities in turbo machines, i.e., surge, rotating stall, cavitation surge and rotating cavitation, and the unified numerical model of these instabilities has been examined and presented. In these studies, the dynamic behavior of pressure oscillation was evaluated mainly by the equation of continuity on the supposition that the fluid was “incompressible.” The unsteady characteristic of cavitation was expressed as a mass flow gain factor M and cavitation compliance K, and then the frequency of pressure oscillation was expressed as the Helmholtz frequency, $1/(\rho KL/A)^{1/2}$, where ρ is the density of fluid, K is the cavitation compliance, L is the length of the inlet pipe and A is the area of the pipe. According to the current analytical model, when the inlet pressure is decreased, cavitation compliance K becomes large and the natural frequency of the cavitation surge decreases continuously.

However, when the improved liquid oxidizer turbopump of LE-7A engine was experimented in JAXA's turbopump test facility, it was found that the frequency of cavitation surge was higher than the calculated frequency with the current analytical model. In addition, the frequency of cavitation surge varied discontinuously when the inlet pressure of turbopump was decreased. The liquid rocket propulsion system of the H-IIA rocket is equipped with a PSD (POGO Suppression Device), which is a kind of surge tank possessing a function of hydraulic compliance and is installed in upstream of the liquid oxidizer turbopump. The purpose of PSD is to avoid POGO instability, lowering the first characteristic frequency of the inlet pipe to lower the structural resonant frequency. For the purpose of evaluating the stability of the propellant feed system, PSD was added to the turbopump test facility and several tests were carried out. Consequently, it was found that even if the cavitation number was decreased, the frequency of cavitation surge remained constant at a certain cavitation number. The frequency then decreased to some extent, but it again remained constant at another cavitation number. Thus, the experimental result of using the PSD was different from the result without PSD. The frequency of the cavitation surge generated while testing without PSD became integral multiples of two minutes of the acoustic natural frequency in piping. Moreover, the constant frequency at a certain cavitation number while testing with PSD was integral multiples of two minutes of the acoustic natural frequency. The cavitation surge, which occurred in the turbopump test, seemed to be a kind of the acoustic resonance phenomenon. Therefore, we considered the factor of "compressible" fluid and employed analyses applying an acoustic model, combining the inlet pipe with the sonic velocity of liquid oxygen.

Firstly, we carried out a one-dimensional linear analysis using a frequency-domain method to understand the phenomenon of the acoustic cavitation surge. The analytical model consisted of a tank, an inlet pipe and a turbopump on the supposition that the fluid was "compressible." We simplified the model by omitting the small branches in the inlet pipe and the unsteady flow in the discharge pipe of the turbopump. Although a certain capacity usually existed in the exit of pipeline, it was not taken into account in this model because the cavity volume in the turbopump had a capacity to some extent. In other words, a dynamic gain of the turbopump was neglected to simplify this model. From the characteristic equation of the analytical model, solutions of complex frequency ($\omega_R+j\omega_I$) were obtained, where ω_R was the frequency of cavitation surge and ω_I was the damping rate, i.e., when the value of ω_I was positive, the cavitation surge was stable. According to the analytical result, when cavitation compliance K was treated as a parameter, the frequency of cavitation surge slightly decreased along with the decrease in cavitation compliance K. This result was understood as follows. When cavitation compliance K was small, the inlet pipe had an open boundary condition on the tank side and a closed boundary condition on the turbopump side. Therefore, the frequency of cavitation surge became close to (2n+1)/4 times the acoustic fundamental frequency. On the other hand, when cavitation compliance K was large, the frequency of cavitation surge became close to n/2 times the acoustic fundamental frequency because both ends of the pipe had open boundary conditions. As the inlet pressure decreased, cavitation compliance K became large and the boundary condition at the turbopump changed from a closed state to an open state. Consequently, the frequency of the cavitation surge slightly decreased with the reduced inlet pressure. In this way, when the inlet pressure of the turbopump decreased, the operating turbopump performed as an intermediate boundary condition between an open and a closed state. When mass flow gain factor M was treated as a parameter, the frequency of cavitation surge ω_R was not affected at all by the value of mass flow gain factor M. On the other hand, the damping rate ω_I always became negative when mass flow gain factor M was positive. Thus, the acoustic cavitation surge became unstable when mass flow gain factor M was positive. When the drag coefficient in the pipe K_{drag} was treated as a parameter, the value of the damping rate ω_I increased by half the number of K_{drag}, i.e., when the value of K_{drag} was 6, the value of damping rate increased by 3 (= 6 ÷ 2). From the results of these trend analyses, we found that (1) the boundary condition on the turbopump side was incompletely open and cavitation compliance K determined cavitation surge frequencies, (2) positive mass flow gain factor M caused the system to be unstable, and (3) friction K_{drag} made the system more stable.

The values of cavitation compliance K and mass flow gain factor M of the operating turbopump were necessary to calculate the analytical model; therefore, steady state CFD (Computational Fluid Dynamics) analyses on the inducer were conducted to obtain cavitation compliance K and mass flow gain factor M. The cavity volume in the inducer under a certain inlet pressure was obtained by steady-state CFD analysis and another cavity volume under a different inlet pressure was obtained as well. Consequently, the quasi-steady value of cavitation compliance K could be estimated using these two results of CFD analyses. The quasi-steady value of mass flow gain factor M was estimated by the same method. By using the estimated cavitation compliance K and mass flow gain factor M, the frequency ω_R and damping rates ω_I were obtained by the analytical model, and the result of the analysis without PSD provided harmonic frequencies of acoustic resonance in the inlet pipe. The agreement of the frequency between the experimental result and analytical result was fairly well. Furthermore, the frequency of the analytical result slightly decreased with the reduced cavitation number as did the result of the experiment, which meant that the boundary condition of the turbopump side actually varied from a closed state to an open state. The value of K_{drag} of the turbopump test facility was very small (about 0.6), on the other hand, those of the other test facilities were very large (the range was between from 3 to 5). From the result of parametric study on K_{drag}, damping rates ω_I increased by half the number of K_{drag}, then became positive when the turbopump was tested in the other facilities. This result proved that the cavitation surge was not occurred in the other test facilities with the same turbopump.

According to the analytical result with PSD, when the cavitation number was decreased, the frequency of the cavitation surge remained constant to a certain cavitation number. The frequency then changed suddenly to some extent, but again kept constant at another cavitation number. Although there was a small disagreement with the cavitation number, the analytical result qualitatively corresponded with the experimental result. When cavitation compliance K was treated as a parameter in the analytical model with PSD, the frequency of cavitation surge decreased discontinuously as cavitation compliance K increased, i.e., the cavitation number decreased. Although the cavitation surge without a PSD became unstable over a wide range of cavitation compliance K, the cavitation surge with the PSD only became unstable when the Helmholtz frequency between the turbopump and the PSD $\{=1/(\rho KL/A)^{1/2}\}$ coincided with one of the acoustic modes of the inlet pipe. In short, Helmholtz oscillation between the turbopump and the PSD resonated with acoustic modes of the inlet pipe between the tank and the PSD. Consequently, it was found that when the PSD was installed upstream in the turbopump, the frequency of cavitation surge became dependent on the Helmholtz frequency between the turbopump and the PSD. When the frequency coincided with one of the acoustic resonances of the inlet pipe between the tank and the PSD, the cavitation surge resonated and maintained its frequency within a certain range of cavitation number.

The result of linear analysis, however, could not explain the phenomenon that the frequency of cavitation surge changed from an acoustic natural frequency to another natural frequency at a certain cavitation number in the tests without PSD. The cause was thought not to include the influence of the nonlinear factors, i.e., the large amplitude of pressure oscillation and the drag of piping which was proportional to the square of the speed of the fluid. Therefore, we carried out one-dimensional analysis using time-domain method to take into account the nonlinear factors. From the nonlinear analysis, it was found that the cavitation surge was weakened by the nonlinear factors (the limitation of pressure amplitude by the vapor pressure of liquid oxygen and the resistance of the piping) and then the amplitude of pressure oscillation remained constant. The boundary condition of the turbopump side became close to an open state as the cavitation number became lower and as the frequency became higher. As a result, the damping effect to the cavitation surge grew due to the lower cavitation number and the higher frequency. The nonlinear analytical result could simulate the phenomenon that the oscillation of a higher frequency mode was weakened and disappeared at a certain cavitation number, and the oscillation of a lower frequency appeared instead. Thus, this analytical result agreed with the experimental result qualitatively.

From findings obtained from the analytical result, we expected that the frequency of the cavitation could be controlled by adjustment of the distance of PSD and the turbopump. Although cavitation surge was observed in the improved liquid oxidizer turbopump test, development of the turbopump was continued, and it was found in the engine firing tests that the frequency of cavitation surge became very high by shortening the distance between PSD and turbopump. Furthermore, the cavitation surge did not resonate with all the characteristic frequencies of the rocket and the amplitude of pressure oscillation became small compared with the one observed in the turbopump test. Evaluating the results of the development tests, it was decided to apply the improved liquid oxidizer turbopump to the H-IIA rocket and the flight of launch vehicle was successful.

論文審査結果の要旨

H-IIAロケット第1段エンジンの改良型液体酸素ターボポンプの開発試験中に，キャビテーションサージの変動周波数が従来の解析モデルで予測される周波数よりも高く，かつキャビテーション数の低下に対して連続的には変化せずに，あるキャビテーション数で不連続となる現象が観察された。本研究では，従来の解析モデルでは説明がつかなかった，周波数が高くかつ不連続となるキャビテーションサージ現象を解明することを目的として，推進剤を供給する配管内の流体の圧縮性を考慮して，音響的な効果を解析モデルに取り入れることを提案している。また解析結果と試験結果の比較検証を行い，今後のロケットエンジンシステムの共鳴キャビテーションサージへの対策法を提言している。本論文は，これらの研究成果をまとめたものであり全編6章からなる。

第1章は序論であり，本研究の背景，目的，及び構成を述べている。

第2章では，ターボポンプの単体試験で発生した，共鳴キャビテーションサージ現象の観察結果を論じている。共鳴キャビテーションサージは，実験室レベルのキャビテーションサージとは様相が異なるものであって，ターボポンプの実作動条件下のみで生じうる事象であることを明らかにしており，これは重要な知見である。

第3章では，ターボポンプに推進剤を供給する配管内の流体の圧縮性を考慮することによって，配管の音響効果を考慮した周波数領域の線形解析モデルを構築している。この解析結果によって第2章で観察された共鳴キャビテーションサージ現象を定性的に説明できることを示している。これは従来の非圧縮を仮定した慣性モデルでは説明がつかなかった共鳴キャビテーションサージ現象の解明に資する重要な成果である。

第4章では，線形解析モデルでは再現できなかった，共鳴キャビテーションサージの周波数があるキャビテーション数で不連続となる現象の解明を目的として，時間領域の非線形解析モデルを構築している。この解析結果により，周波数が不連続に飛躍する試験結果が説明できるようになり，かつシステムの安定／不安定の判別だけでなく，圧力振幅値についても試験結果とほぼ一致することを示している。これはターボポンプシステムに生じるキャビテーションサージ現象を予測する手法の構築として重要な成果である。

第5章では，第4章までの考察をもとに実際のロケットでの共鳴キャビテーションサージ現象を抑制するためには POGO 抑制装置の配管システム上での設置位置が重要であることを提言している。さらに，その抑制法がロケットエンジンの燃焼試験及び実際のロケットの打ち上げ時の作動においても有効であることを解析結果と試験結果の比較検証によって示しており，これは今後のロケットの打ち上げ時の作動に関する重要な知見である。

第6章は結論である。

以上要するに本論文は，従来流体を非圧縮と仮定して行われていた実験室レベルのキャビテーションサージの解析とは異なり，実際のターボポンプは回転数が高く，推進剤の音速は水に比べて遅く，かつ管路長が長いためターボポンプの試験システム及び実際のロケットシステムでは配管内の流体の圧縮性を考慮に入れる必要があることを，諸々の試験結果及び新しく構築した解析モデルから考察し，それらの結果よりロケットエンジンシステムの共鳴キャビテーションサージの抑制法を示したものであり，航空宇宙工学及び流体工学の発展に寄与するところが少なくない。

よって，本論文は博士（工学）の学位論文として合格と認める。